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High-Power Laser Diodes at Various Wavelengths

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ABSTRACT

High power laser diodes at various wavelengths are described. First, performance and reliability of an optimized large transverse mode diode structure at 808 and 941 nm are presented. Next, data are presented on a 9.5 kW peak power array at 900 nm having a narrow emission bandwidth suitable for pumping Yb:S-FAP laser materials. Finally, results on a fiber-coupled laser diode array at ~730 nm are presented.

Keywords: laser diode, InAlGaAs, AlGaAs, COD, Yb:S-FAP, Yb:YAG, PDT

1. OPTIMIZED LARGE-MODE LASER DIODE STRUCTURE

Reliability and catastrophic optical damage (COD) levels of laser diodes are determined in large part by the optical intensity at the facets. One approach to reducing the intensity at the facets is to design the diode transverse waveguide structure such that the mode width is large, thus effectively spreading the intensity over a larger area and reducing the facet loading. We have described such a structure, only partially optimized, previously[1]. A more fully-optimized version of this structure is given in Fig. 1. There the device is seen to

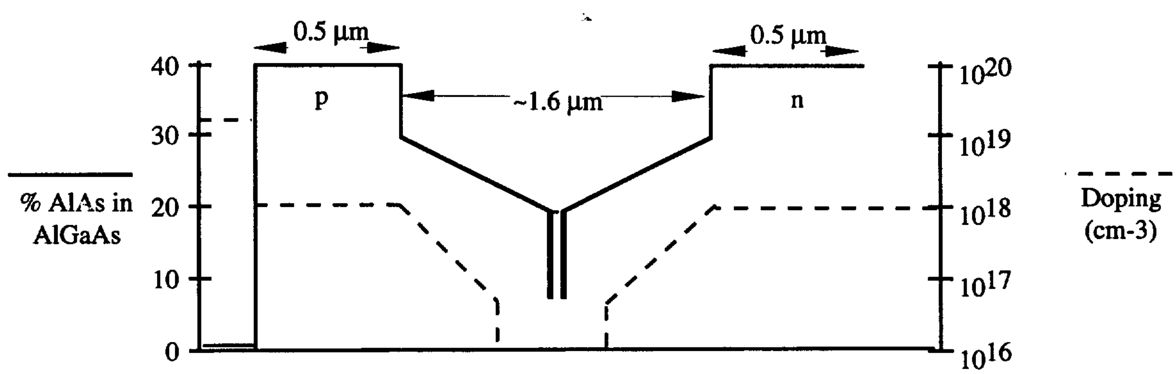

Figure 1. Optimized large-mode laser diode structure.

have characteristics of both conventional graded-index separate confinement (GRINSCH) and large optical cavity separate confinement heterostructure (LOC-SCH) structures. The band gap step between the cladding layers and the edges of the graded regions serves to improve carrier confinement, while the graded region both enhances carrier collection in the quantum wells and reduces the strength of the waveguide, compared to a standard LOC-SCH, so as to enlarge the optical mode. Doping concentrations are also given in Fig. 1, and the doping is seen to taper down as the active region is approached so as to minimize free carrier absorption losses, thus increasing differential quantum efficiency (DQE) and reducing the mode loss[2]. This device has been investigated at both 808 ($In_{.10}Al_{.15}Ga_{.75}As$ wells) and 941 ($In_{.14}Ga_{.86}As$) nm, with the structure identical at both wavelengths except for the composition of the 70Å quantum wells. It was found that for both wavelengths that and active region comprising two quantum wells provided good performance for pulsed operation with pulse widths up to 400 μsec and duty factors up to ~25%, but cw operation required three wells in order to avoid thermal rollover even at low power levels. Typical performance for uncoated, unmounted 100 x 500 μm devices having three quantum wells, under pulsed conditions of 10 Hz, 100 μsec are j_{th}=490 A/cm^2 and DQE=81% at 808 nm, and j_{th}=415 A/cm^2 and DQE=86% at 941 nm.

In order to assess the reliability of these structures, 1 cm x 1000 μm bars, having 100 μm emitters at a 71% fill factor were fabricated. The bars were coated and bonded to microchannel heatsinks[3] for high average power evaluation. Reliability testing was done at a constant power of 100 W peak per bar using 400 μsec pulses at 500 Hz (20% duty factor) and 10°C coolant, and results for 808 and 941 nm bars are given in Fig. 2. There it is seen that while the 808 nm structure has a projected life (30% degradation) of more than 10^9 shots, the 941 nm device has a projected life of more than 10^{10} shots. Further reliability testing was done under cw conditions with 20°C coolant for the 941 nm structure and is shown in Fig. 3 for various power levels. Operation at 25 and 30 W/cm yields projected lifetimes of greater than 10,000 hours (30% degradation). Operation at 40 W/cm yielded a lifetime of 1,700 hours, which is an encouraging result that is expected to improve as facet coatings are developed further.

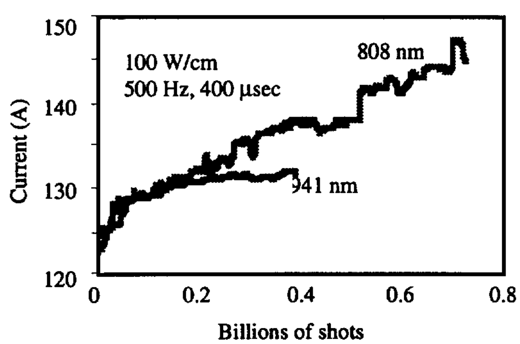

Figure 2. Pulsed reliability results.

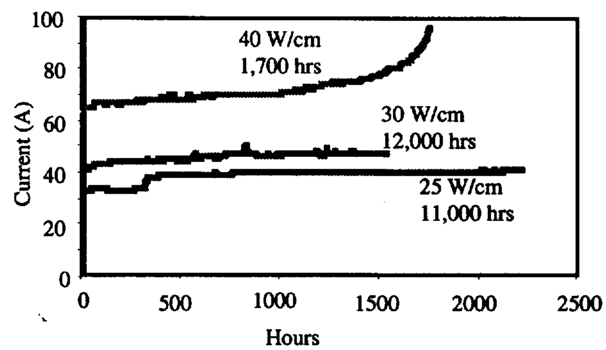

Figure 3. cw reliability results.

2. HIGH-POWER ARRAY AT 900 NM

Ytterbium-doped strontium fluoroapatite ($Sr_5(PO_4)_3F$, or S-FAP) is a new laser material developed specifically for high-energy pulse applications.[4] The appealing aspect of Yb:S-FAP is its fluorescence lifetime of approximately 1 ms, which is approximately 5 times that of the commonly used Nd:YAG system. This ~5-fold increase in storage time allows, for a given Q-switched pulse energy output, 5 times fewer diodes to be used in a Yb:S-FAP system than for a Nd:YAG system. That is, where 5 diodes might be required to pump a Nd:YAG laser for 200 μsec before the desired energy is stored and then Q-switched out, a single diode could pump Yb:S-FAP for 1 ms to store the same amount of energy. Such a reduction in diode requirements is very attractive for high-energy pulsed laser systems, such as for laser fusion.

The pump wavelength for Yb:S-FAP is 900 nm with a FWHM of ~3 nm. The structure of the pump diodes used in this work is shown in Fig. 4. Performance of uncoated, unmounted devices under 10 Hz, 100 μsec pulsed conditions yielded j_{th}=192 A/cm^2 and a DQE of 85%. Coated bars were fabricated (15 mm x 1 mm cavity, 100 μm stripes, 71% fill) and mounted on microchannel coolers, and 96 of these packages were assembled into a pump array. Figure 5 shows that a peak power of approximately 9.5 kW was achieved at 41% power conversion efficiency under 20 Hz, 500 μsec excitation with no evidence of thermal rollover. The emission spectrum of the array is given in Fig. 6 along with the absorption feature, and it is seen that good match is achieved. The 5.7 nm FWHM of the array is approximately broken down into ~2.5 nm "natural" width, ~1 nm of wafer growth variations and ~2.7 nm of chirp during the pulse. Two such arrays were fabricated and used in a high-power Yb:S-FAP laser system.[5]

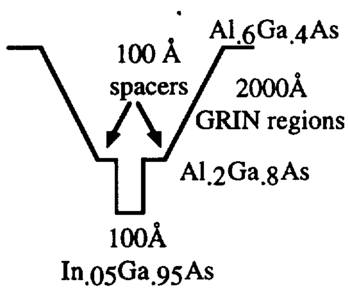

Figure 4. Structure of 900 nm diode.

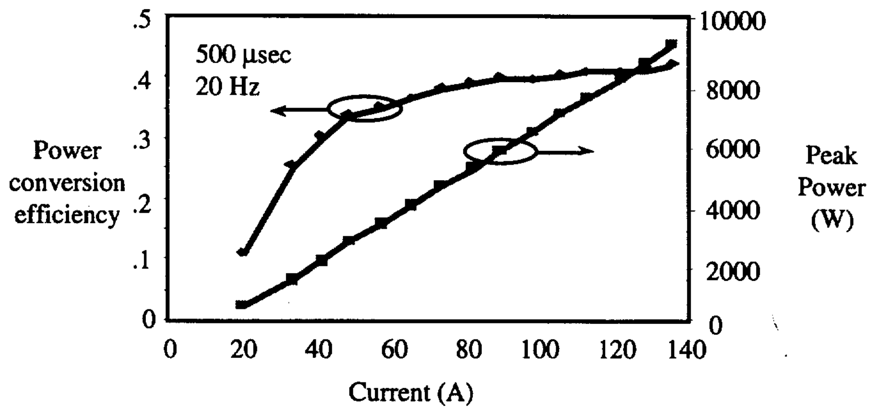

Figure 5. Performance of 900 nm diode array.

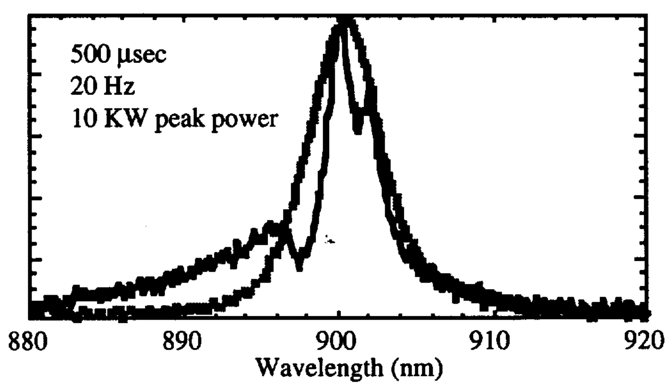

Figure 6. Diode array emission (gaussian) superimposed on the absorption line of Yb:S-FAP.

3. FIBER-COUPLED ARRAY AT 731 NM

In photodynamic therapy (PDT) treatment of cancer, a relatively non-toxic dye is injected into the body and selectively accumulates in cancerous tissue. When optically excited at the proper wavelength, the dye decomposes into toxic products, killing the cancerous tissue while leaving the surrounding tissue unharmed. Approximately 1 W of fiber-delivered cw power is required at the excitation wavelength. A promising dye for this treatment is lutecium texaphyrin which requires excitation at ~731 nm. Presently this wavelength is obtained with cumbersome and expensive argon ion-pumped Ti:sapphire lasers. A laser diode source would be welcome, but in the InAlGaAs/GaAs material system lasers at wavelengths below ~750 nm tend to exhibit poor performance owing to the encroachment of indirect conduction band minima on the direct band gap.

A laser diode structure was developed for 731 nm operation and is shown in Fig. 7. It is a conventional GRINSCH having a single 60 Å $In_{.05}Al_{.24}Ga_{.71}As$ quantum well. The 5% indium in the quantum well is intended to reduce the threshold current and inhibit the formation of dark-line defects.[6] Evaluation of uncoated, unmounted 100 x 500 μm devices under 10 Hz, 100 μsec excitation yielded j_{th}=508 A/cm^2 and DQE=52%. Coated bars were fabricated (5 mm x 500 μm, 100 μm stripes, 71% fill) and mounted on microchannel coolers and fitted with a collimating microlens.[7] When operated at 7°C coolant temperature, these bars exhibited thermal rollover of the L-I characteristic between 5 and 10 W cw output. An array of 5 such bars was assembled at a 1 mm pitch, giving a 5 x 5 mm emission aperture which was focused using a simple lens onto the end of a 0.37 NA fused silica 1 mm core fiber. In this manner[8] a coupling efficiency of ~50% was achieved, and 5 W cw was delivered from the end of the fiber (power was not increased to the rollover point of the array output). An appealing feature of this fiber coupling technique is that the tip of the fiber may be quickly and easily replaced after use; this is an important feature for medical applications. Coupling schemes which are based on bundling"fiberlets" which are coupled to individual emitters do not easily lend themselves to simple replacement of the fiber tip. This fiber-coupled unit is being evaluated in medical trials.

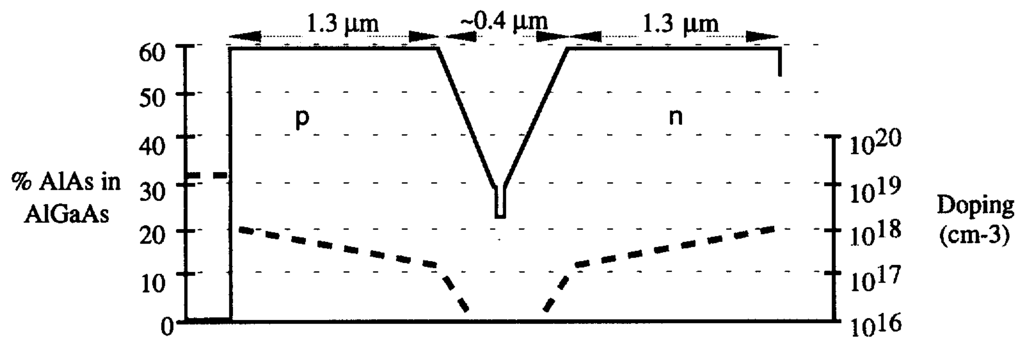

Figure 7. Structure of the 730 nm diode. The quantum well is 60 Å $In_{.05}Al_{.24}Ga_{.71}As$.

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